Water Conservation Options for Wet-Cooled Power Plants

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ABSTRACT

Some areas of the Southwest have been experiencing drought conditions in recent years. If these conditions persist, power plants in such areas may face increasingly stringent water availability limits and the need to reduce their water use. Since the largest use of water at most plants is the evaporation of water in the cooling towers, modifications to, or alternatives to, the current cooling system design and operation will be required. A study was conducted which identified and compared several approaches to reducing cooling water consumption at the Public Service Company of New Mexico's (PNM) San Juan Generating Station, an 1,800 MW coal-fired plant in Farmington, New Mexico.

This approach focuses on the addition of supplemental dry cooling capability to the existing wet cooling tower systems. Alternative arrangements and operating strategies of adding dry cooling are discussed and compared on the basis of capital cost, operating and maintenance costs and effects on plant performance. Another approach, the use of alternative, "non-fresh" sources of water as make-up to the wet towers, is discussed in a paper by DiFilippo at this Workshop.

The conclusions from the study are:

- Significant water savings cannot be achieved through operational modifications to existing cooling systems.
- Supplemental dry cooling can be added in series, parallel or "split-series" arrangements. Water savings of 10% to 30% were achievable with a variety of system design and operational approaches.
- The sum of amortized capital costs, O&M costs and "penalty" or "heat rate" costs resulted in equivalent water costs of $1,700 to $2,600 per acre-foot of water saved.

The use of produced water (water "produced" as a result of oil and gas drilling) from neighboring gas and oil field operations is comparable in cost to the supplemental dry cooling options exclusive of collection and delivery costs.

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Introduction

The Southwestern United States has experienced dry conditions for the past several years. Moreover, as Figures 1 and 2 indicate, these conditions are not unusual for that area based on observations and averages that go back into the 19th Century (Figure 1) and, indeed, back as far as 2100 BP (Figure 2). Therefore, given that the relatively wet conditions of the 1970's and 1980's may not be likely to return, the San Juan Generating Station (SJGS) is considering possible water conservation strategies which might be adopted should drought conditions persist.

The largest use of water at the plant is for make-up to the four cooling towers. Unit 3 is equipped with a water-conserving dry-wet tower, and a study was recently completed to determine the best approach to restore it to original performance levels. It remains to be determined if cost-effective means can be found to reduce the water consumption in the towers on Units 1, 2 and 4 while maintaining an acceptable level of cooling. To this end, a study was initiated in the Spring of 2003 to explore possible approaches to reduce fresh water consumption in the existing wet cooling towers on Units 1, 2 and 4.

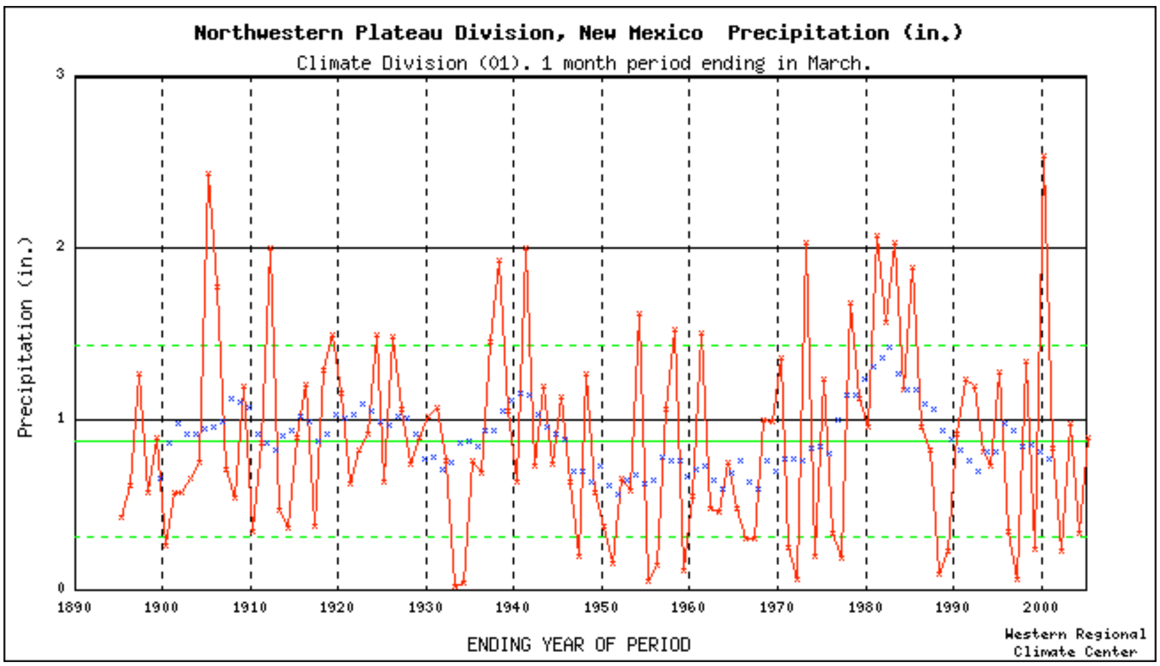

Figure 1: Rainfall in Northwestern New Mexico (1890 –2005) (from [1])

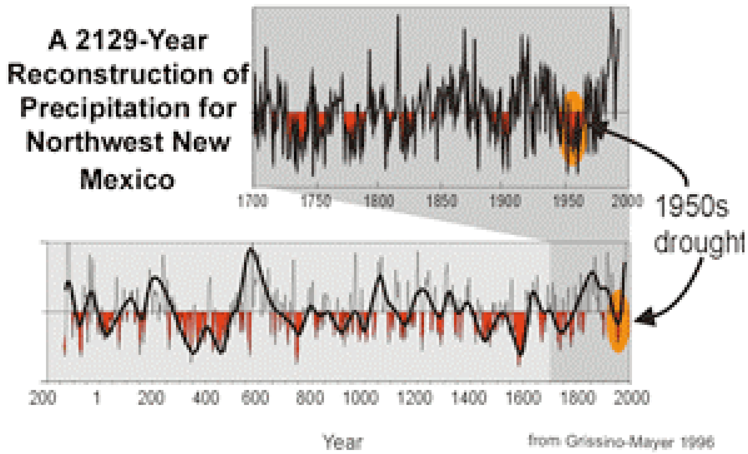

Figure 2: Paleo-Climate Rainfall Records in Northwest New Mexico (from [2])

Three approaches were considered. They were operational modifications to the existing cooling systems, the addition of supplemental dry cooling capability and the use of alternative, "non-fresh" sources of water as make-up to the wet systems.

This paper focuses on the addition of supplemental dry cooling capability to the existing wet cooling tower systems. Alternative arrangements and operating strategies of adding dry cooling are discussed and compared on the basis of capital cost, operating and maintenance costs and effects on plant performance. The use of "non-fresh" water and of equipment suitable for that purpose are discussed in other papers at this Workshop. {[3], [4]}

Site Information

Cooling system performance is determined in part by the characteristics of the plant site. SJGS site elevation is 5,400 feet above sea level. The ambient temperature and humidity vary throughout the year. The temperature duration curves for ambient dry bulb and wet bulb temperatures are shown in Figure 3.

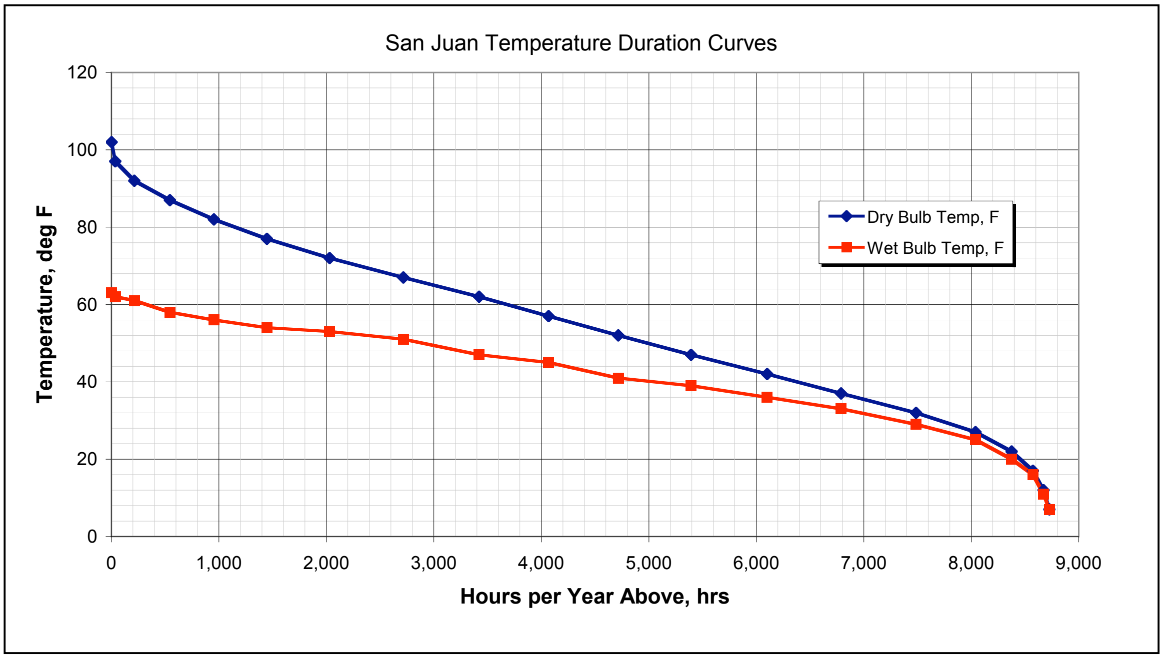

Figure 3: San Juan Temperature Duration Curves (from [5])

<u>Existing Cooling Systems</u>

Units 1, 2 and 4 are currently equipped with wet cooling towers. A brief description and estimated operating points are summarized below:

Units 1 & 2	Unit capacity:	350 MW
(per unit values)	Cooling system:	Marley cross-flow towers
		11 cells, in-line
		Splash fill, Marley Omega Bar
	Performance:	Design wet bulb, 66 F
		Design cold water temperature, 80 F
		Water flow, 170,000 gpm
		Cooling range, 21 F
	Water use:	Evaporation rate, approx. 3,100 gpm
		Cycles of concentration, ~12
		Make-up rate, approx. 3,400 gpm

Unit 4	Unit capacity:	550 MW

Cooling system:	Marley cross-flow tower 16 cells, (2 x 8, in-line) Splash fill, Marley Omega Bar
Performance:	Design wet bulb, 66 F Design cold water temperature, 80 F Water flow 227,500 gpm Cooling range, 23.1 F
Water use:	Evaporation rate, approx. 5,200 gpm Cycles of concentration, ~10 Make-up rate, approx. 5,800 gpm (partially supplied by Unit 3 blowdown)

Figure 4 displays the cold water temperature and the evaporation rate for the Unit 4 cooling tower operating at full load over the annual range of ambient temperatures. The annual evaporation is approximately 7,700 acre feet.

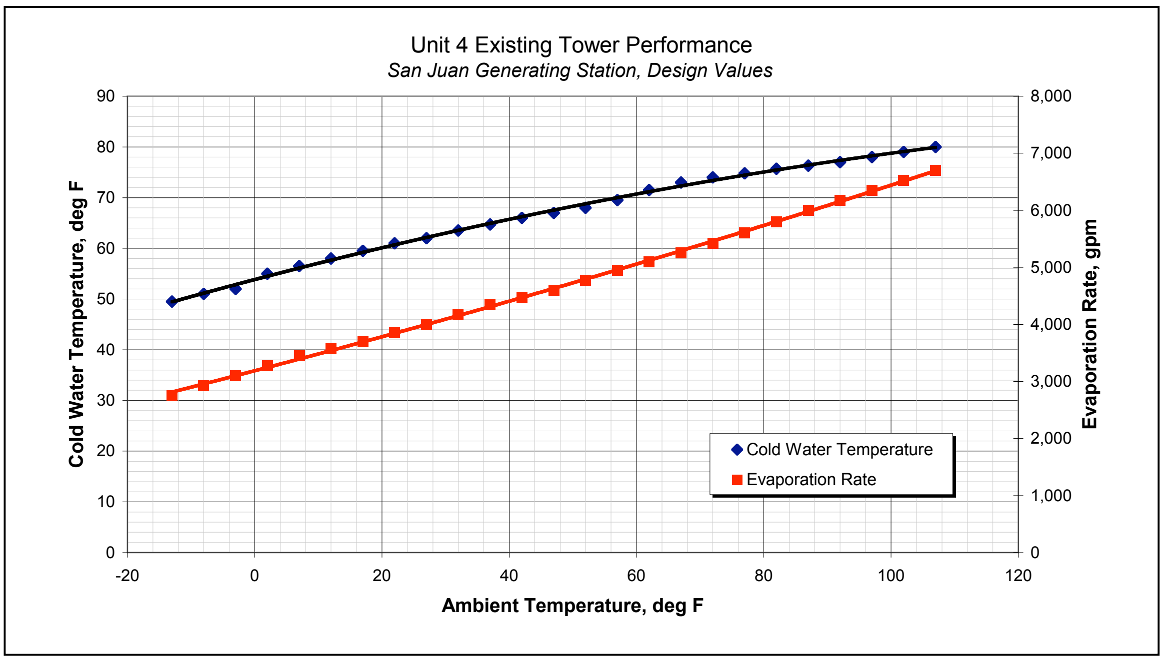

Figure 4: Existing Unit 4 Tower Performance

Supplemental Dry Cooling

In supplemental dry cooling an air-cooled heat exchanger is installed into the existing cooling loop to carry a portion of the cooling load and reduce the existing wet cooling tower's evaporation rate.

The design procedure for achieving a specified annual level of water savings is an iterative one. An initial guess at the size of the supplemental air-cooled heat exchanger is made usually by specifying that it meet a specified portion of the plant cooling load at some ambient temperature. For example, to achieve 20 percent water savings, a unit capable of meeting 20 percent of the heat load at the annual average ambient temperature might be chosen for a starting point. The operation of the existing wet tower, in conjunction with the selected dry exchanger to deliver the required cold water temperature is then calculated for all times of the year using the site temperature duration curves (Figure 3). The total water use is then determined. If this is close to the desired savings, the design is complete. If not, the size of the air cooled exchanger is changed, and the process repeated, until a satisfactory savings is achieved.

Cooling Loop Arrangement

The dry exchanger can be installed in series or in parallel with the wet tower. These primary alternative arrangements are shown in Figures 5 and 6. Figure 7 shows a combined approach referred to as “split series”. Each arrangement has advantages and disadvantages. The series arrangement results in a smaller heat exchanger for a given heat load since the greatest amount of the cooling water is transferring heat to the atmosphere at the highest temperature. However, the additional pumping power required to pump the full flow through the air-cooled exchanger is added to that required to lift the full flow to the top of the wet tower.

On the other hand, a parallel arrangement results in a larger air-cooled exchanger for a given heat load but requires less pumping power since the flow through the air-cooled exchanger can be returned to ground level basin of the wet tower. In this arrangement the hydraulics of the water flow in the wet tower is altered as a result of the reduced flow with some effect on thermal performance.

The “split series” arrangement retains some of the thermal advantages of the series arrangement and some of the pumping power reduction of the parallel arrangement while leaving the hydraulics of the wet tower unaffected.

Desired Cold Water Temperature

With the additional cooling capacity of a supplemental dry cooling unit in place, it is possible to manipulate the operation of the wet tower to modulate the temperature of the cold water that is returned to the steam condenser. The choice can range from maintaining the existing cold water temperature profile to keeping it at the design point (80 F, in this case) year round or delivering colder water than was possible with the existing wet tower alone. In general, the lower the cooling water temperature, the more water must be evaporated in the wet tower and the more operating power will be consumed by the fans on the wet tower. The choice depends on the relative value of lower temperature water in the form of reduced turbine heat rate versus the value of additional water savings.

To achieve the various cold water temperature profiles, the operation of the wet tower must be modulated. As the ambient dry bulb temperature decreases, the air-cooled exchanger bears more of the load and the wet tower receives cooler and cooler water (in a series flow arrangement). It is possible to turn off more and more fans on the wet tower as the temperature goes down while still maintaining a constant cold water return temperature with a consequent reduction in the wet tower evaporation rate. This is similar to the original design concept for the hybrid dry/wet tower on Unit 3.

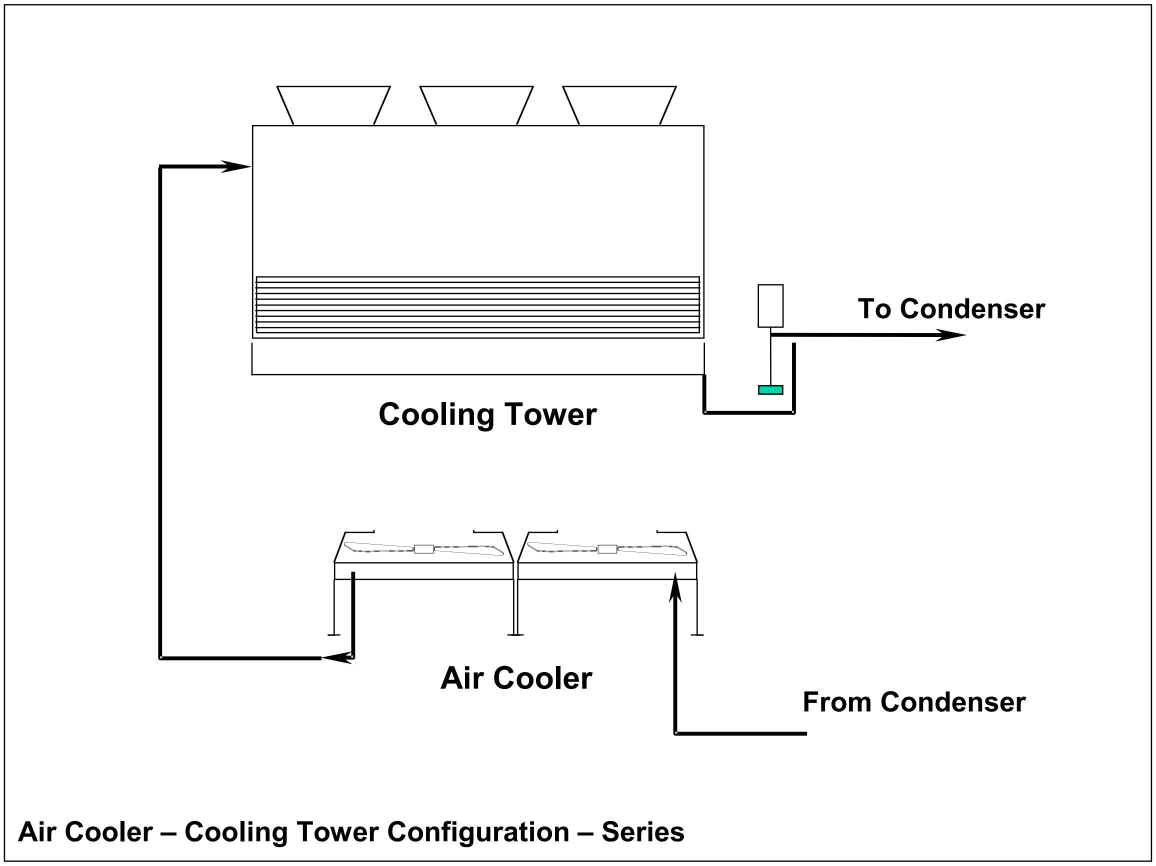

Figure 5: Series Arrangement

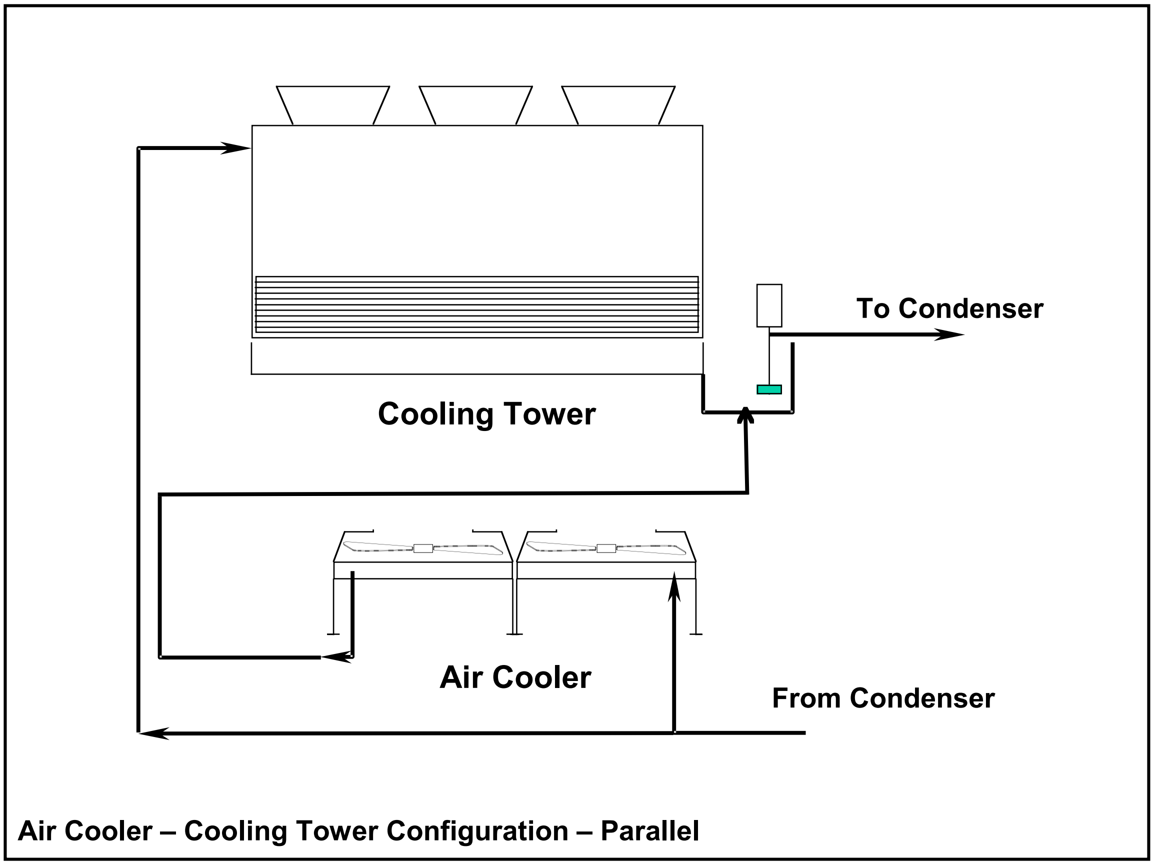

Figure 6: Parallel Arrangement

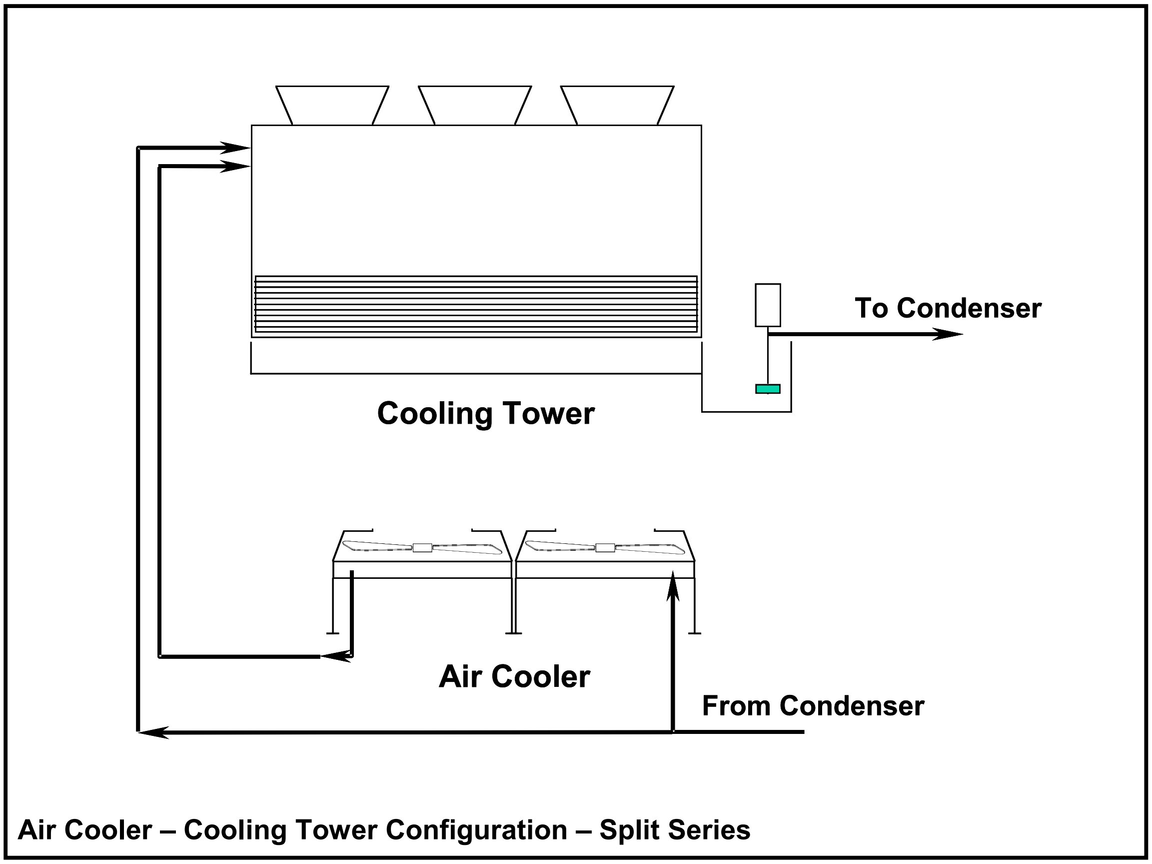

Figure 7: Split Series Arrangement

Comparative Analyses

Different approaches, designated as A, B, C and D, were developed based on information from four equipment suppliers. In all but one case, the results for equipment cost, water use, power requirements and cold water temperature were provided by the suppliers based on requests and specifications provided to them. In one case (B), the results were developed by the authors using a design and calculation routine entitled "Basics of Air-Cooled Heat Exchangers" available on a vendor website.

In all cases, designs and operating profiles were requested that would achieve nominal water savings of 10, 20 and 30% of the current consumption by the existing towers. A variety of approaches were taken. The choices of cooling system arrangement and operating strategy are listed in Table 3. A brief description of the approaches and results from the various sources and analyses follows.

Source	Arangement	Wet Tower Operation	Cold Water Delivered
A	Series	Modulated	Design temperature 80 F year round
B	Series	Full	Close to current profile
C	Series	Full	Close to current profile
D	Split series	Modulated	Match current profile
E	Various	Various	Various--similar to Unit 3

Table 1: Cooling System Arrangement and Operating Strategy

Figures 8, 9 and 10 show some of the more important results of the analyses.

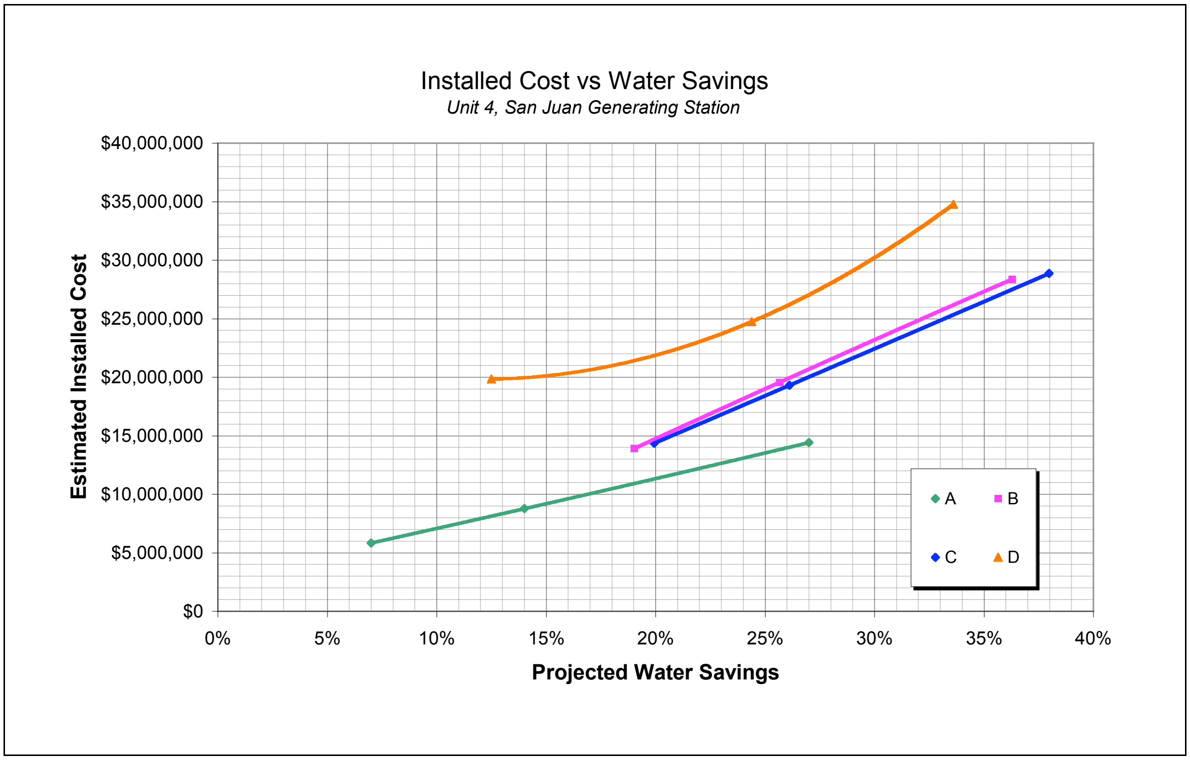

Figure 8: Installed Cost vs. Water Savings

A, B and C are all series arrangements. Case A maintains the cold water temperature at 80 F all year long, allowing the wet tower fans to be turned off sequentially as the ambient temperature falls. Both Cases B and C, also series arrangements, run the wet towers at full capacity throughout the year achieving lower cold water temperatures during the colder periods. Case D is a split-series arrangement, and the wet tower is modulated to simulate the existing system cold water annual temperature profile.

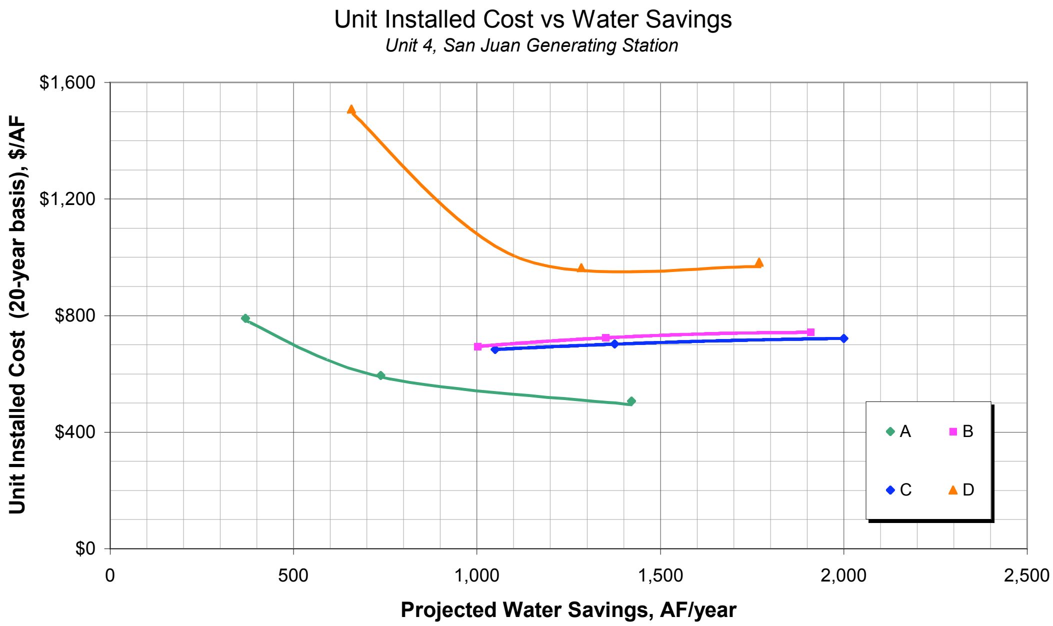

Figure 9: Cost per Acre-foot vs. Water Savings

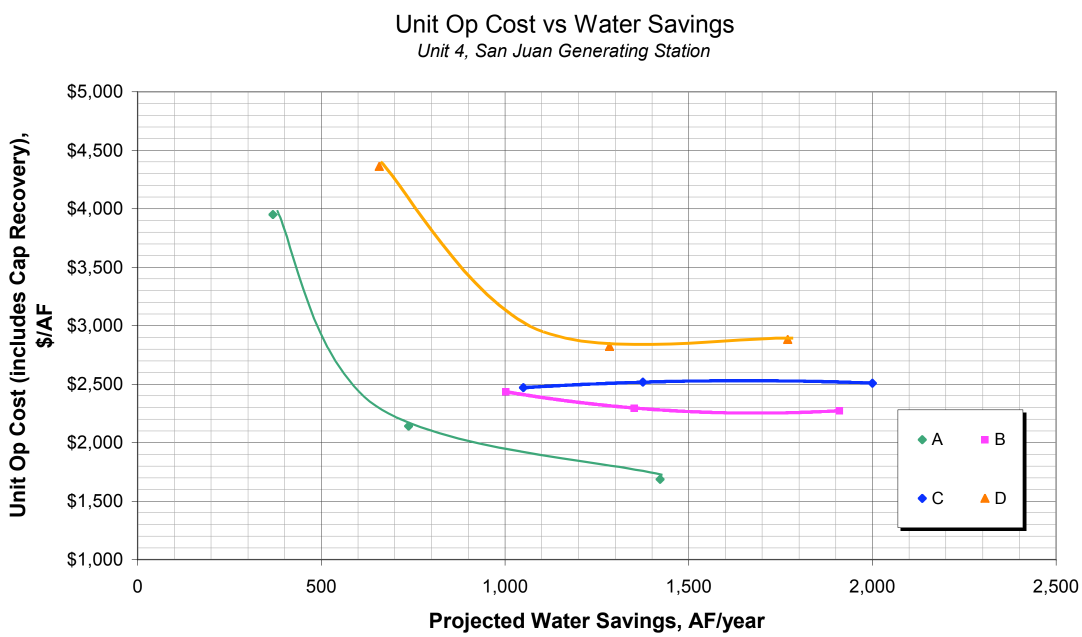

Figure 10: Operating Cost vs. Water Savings

The following observations can be made.

- With the exception of a sharp upturn in the cost per acre-foot at the lowest water savings rates, the slope of the curves of installed cost vs. water savings are quite similar (See Figures 8 and 9). The upturn at low capacities is characteristic of much process equipment which is made up of a fixed cost plus a variable cost which is proportional to size and capacity.
- Cost differences among the approaches are directly attributable to the effect of basic design choices – split series vs. series arrangement and cold water temperature profiles. Approach A, which maintains the cold water temperature at 80 F throughout the year, has a much higher driving temperature difference across the air-cooled exchanger resulting in a smaller (less costly) exchanger for the same heat duty. Similarly, the split series arrangement results in a lower water flow through the air-cooled unit, and therefore, a larger temperature drop for the same heat load. This reduces the Log Mean Temperature Difference (LMTD) resulting in a larger (more costly) exchanger. The cost ratios shown are roughly the same as the ratios of the driving temperature differences (inversely proportional to the exchanger sizes) as would be expected.

Similar arguments apply to the operating costs shown in Figure 10 as normalized operating cost ($/acre foot of savings) versus the projected annual water savings. The trade-offs between capital cost and power costs lead to similar optimum operating costs, which include the capital recovery charge for three of the four approaches. The high water temperature maintained in the fourth approach leads to an overall less expensive system when the capital and power costs are combined into a normalized operating cost.

Comparison of Results

Cost information from the various sources was typically base equipment cost only. Additional costs for transportation, installation (including site preparation and foundation construction), electrical wiring, circulating water piping modifications, pumps and valves, freeze protection, and other items were added through factors and engineering judgment. Additional allowances were added for PNM indirect costs as well as a contingency allowance for cumulative uncertainties. The following adjustments were made for purposes of a uniform comparison:

- 15% additional bare tube area was added to the B and C air cooling systems to compensate for capacity lost from fin fouling.
- An erection factor of 38% was used for all estimates.
- An allowance of 5% (of installed cost) was allowed for civil work.
- An Emergency Drain system (EDS) for freeze protection was added to the costs of all air cooled systems. It included 2 emergency drain pumps, drain piping and a relief valve for each cooling section.

- Other Unit 1, 2 or 4 improvements include:
    - Circulation system modifications – 500 feet per unit of circulation pipe extensions to air coolers at $2,000 per foot to install

    - Circulation pumps – modify 2 pumps (operate at higher head and larger motor) per unit at a cost of $250,000 per pump for modifications/ replacement
    - New electric load center (MCCs) for air cooler fans
- 20-year projected life for the air cooled heat exchangers.
- Annual maintenance costs were assumed to be 3% of equipment cost for those units with a large number of smaller fans. 1.5% was assumed for the others.
- Total Installed Cost includes G&A/sales tax that was assumed to be 11% and contingency/finance charges assumed to be 10% for a total charge of 21%.

Table 2 displays a summary of cost and power requirement information for a single case (Unit 4 cooling system) from each of the four analyses. They were selected to give as nearly as possible the same water savings for a consistent comparison.

The following points are noteworthy.

1. There are significant differences in air-cooled heat exchanger equipment costs and additional power requirements for similar water savings among the various approaches. Costs range from $14.4 million to $23.2 million and power requirements range from 2,400 to 5,400 HP.
2. Equipment costs represent from 30 to 40% of the total installed cost. The largest items are the cost of on-site erection and the cost of modifications and additions to the circulating water system.
3. The range of annual operating costs, while significant (+/- 10% around the average) is considerably less than the variation in equipment costs (+/- 25% around the average). This is due primarily to the lower power and capacity replacement costs for the highest capital cost alternatives.

Summary Comparisons for Unit 4				
San Juan Generating Station				
		Supplier		
	A	**B**	**C**	**D**
Configuration	**Series**	**Series**	**Series**	**Split**
Water Savings, %	**27.0%**	**25.7%**	**26.1%**	**24.4%**
Waer Savings, AF/yr	**1,422**	**1,351**	**1,375**	**1,284**
Water Savings, AF/yr/MW	**2.6**	**2.5**	**2.5**	**2.3**
Foot Print Area, sq. ft.	**43,056**	**44,425**	**42,336**	**39,585**
AC Fan Powr, HP	3,200	3,588	4,400	4,054
Add'l Pumping Power, HP	236	1,086	1,005	640
Wet Tower Power Reductin, HP	-1,074	0	0	-754
Total Add'l Power, HP	**2,362**	**4,674**	**5,405**	**3,940**
Avg Cold Water Temp, F	80.0	68.7	68.7	67.4
Avg Backpressure, "Hg	2.57	1.88	1.88	1.77
Avg Heat Rate Increase, %	0.17%	0.01%	0.01%	0.00%
Add'l Coal Consumed, TPY	**3,444**	**249**	**249**	**0**
Equipment Cost	**$4,000,000**	**$6,818,000**	**$6,401,000**	**$9,290,000**
Total Installed Cost	**$14,410,000**	**$19,562,000**	**$19,306,000**	**$23,232,000**
Power Cost @ $0.025/kWh	$297,000	$587,000	$679,000	$495,000
Power Replmt Cost @ $15/MWh	$178,000	$352,000	$407,000	$297,000
Maintenance	$479,000	$243,000	$479,000	$288,000
Add'l Coal Consumption	$29,000	$2,000	$2,000	$0
Capital Recovery @ 7.5%	$1,414,000	$1,919,000	$1,894,000	$2,279,000
Annual Operating Cost	**$2,397,000**	**$3,103,000**	**$3,461,000**	**$3,359,000**
Unit Op Cost, $/AF	**$1,686**	**$2,296**	**$2,517**	**$2,615**

Table 2: Summary of Comparisons for Unit 4

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